

REVIEW OF α_S MEASUREMENTS

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We present a review of measurements of α_S . The individual measurements are discussed and intermediate averages for classes of related measurements are found. The final average is built using the intermediate values. Correlations are treated consistently. The ICHEP 2006 world average is $\alpha_S(m_{Z^0}) = 0.1175 \pm 0.0011$ dominated by the recent result from lattice QCD.

1. Introduction

QCD is a highly predictive theory, because all processes involving strong interactions must be described by QCD with a universal parameter, the strong coupling constant α_S . Vice versa, all determinations of α_S using different processes must yield the same results once different momentum scales or renormalisation schemes are taken into account. A systematic comparison of measurements of α_S thus is a strong test of the theory.

Averages of different measurements of α_S are calculated with proper treatment of correlations from common uncertainties¹. Uncertainties are classified as statistical, experimental, soft QCD or hard QCD. Statistical and experimental uncertainties stem from limited data samples and experimental systematics. Soft QCD uncertainties stem from hadronisation correction systematics, higher twist effects, influence of parton density functions (pdfs) and other non-perturbative effects. Hard QCD uncertainties arise from unknown or incomplete higher order corrections.

All results, intermediate averages and the final average are shown in table 1. The intermediate averages of α_S from related analyses are found assuming uncorrelated statistical errors, partially correlated experimental and soft QCD errors and fully correlated hard QCD errors¹. Results with total error on $\alpha_S(m_{Z^0})$ significantly larger than

0.01 have not been considered.

2. Lattice QCD

New implementations of unquenched lattice QCD (LQCD) with dynamical staggered light quarks (u, d and s) improve significantly the description of some low energy observables² after tuning the simulation with precisely known hadron masses and mass differences. Due to quark staggering quark vacuum polarisation loops contribute 4-fold and the procedure has to be modified by hand to compensate this effect. The tuned LQCD is used to predict 28 selected short distance observables which in turn are compared with NNLO QCD calculations to extract α_S ³. The uncertainties of the result are dominated by limited simulation statistics and systematic uncertainties of the analysis. With this measurement a 1% accuracy for a determination of $\alpha_S(m_{Z^0})$ is reached.

3. DIS Processes

The analyses of scaling violation of structure functions (SFs) in deep inelastic scattering (DIS) of leptons on nucleons result in precision measurements of α_S . The scaling violation of the SF F_2^{ep} in e-p DIS was studied in moment space in NNLO QCD but lacks a full analysis of the theoretical error⁴. Following⁵ the theory error is doubled. The SF F_3^ν for neutrino-nucleon DIS was anal-

ysed using Mellin moments and Jacobi polynomials in NNLO QCD ⁶. The SF g_1^N for DIS with polarised nucleons N was analysed in NLO QCD ⁷.

QCD predictions for some sum rules (SRs) in DIS are available in NNLO. The study of the Bjorken SR for polarised DIS ⁸ yields a precise value of α_S but the analysis of the experimental error has been criticised ^{9,10}; we double this error for our averages. The GLS SR for ν -N DIS was studied using CCFR data ¹¹.

The more recent determinations of α_S from jet production in e-p DIS (J. Terron, these proceedings) are NLO QCD analyses covering a wide range of Q^2 values. The comprehensive combination of HERA results for this process is used ¹².

4. Y Decays

The Y resonances are $b\bar{b}$ bound systems with mass dominated by the large b quark mass. Properties of these systems are predicted with non-relativistic QCD (NRQCD) which takes the low velocities of the heavy quarks as an additional expansion parameter. Moments of $R_b(s = m_Y^2) = \sigma(e^+e^- \rightarrow b\bar{b})/\sigma(e^+e^- \rightarrow \mu^+\mu^-)$ ¹³ and the branching ratio $R_{Y \rightarrow \gamma\gamma} = \Gamma(Y \rightarrow \gamma + \text{hadrons})/\Gamma(Y \rightarrow \mu^+\mu^-)$ ¹⁴ have been predicted in NRQCD and used to extract α_S .

5. R_τ

For hadronic decays of τ leptons the invariant mass s of the hadronic final state sets the energy scale for QCD processes. The hadronic branching ratio $R_\tau(s) = \Gamma(\tau \rightarrow \nu_\tau \text{hadrons})/\Gamma(\tau \rightarrow \nu_\tau \nu_\ell \ell)$ is predicted in NNLO QCD while non-perturbative effects are treated with the operator product expansion (OPE). Using τ decay data from ¹⁴ the determination of α_S is updated ¹. A recent analysis using the partially calculated NNNLO term is consistent but claims smaller uncertainties ¹⁵.

6. Z Lineshape

The precise data collected by the LEP experiments and SLD around the Z^0 resonance yield an accurate determination of $\alpha_S(m_{Z^0})$ via QCD corrections to electroweak processes. The analysis ¹ with data from ¹⁶ uses as observables the hadronic width Γ_h and the hadronic branching ratio $R_{Z^0} = \Gamma(Z^0 \rightarrow \text{hadrons})/\Gamma(Z^0 \rightarrow \ell\bar{\ell})$ of the Z^0 and the on-peak hadronic and leptonic cross sections. The result is consistent with ¹⁶ and has a more complete error analysis.

7. F_2^γ

The scaling violations of the SF F_2^γ for hadron production in two-photon interactions at e^+e^- colliders has been studied with NLO QCD. With recent data from LEP at high and low Q^2 a stable result with small errors is obtained ¹⁷.

8. R_{had}

The analysis of hadron production in e^+e^- annihilation at low $\sqrt{s} < 2$ GeV uses the observable $R_{\text{had}}(s) = \sigma(e^+e^- \rightarrow \text{hadrons})/\sigma(e^+e^- \rightarrow \mu^+\mu^-)$. The NNLO analysis ¹⁸ yields a fairly accurate result with errors dominated by experimental uncertainties.

9. e^+e^- Jets and Event Shapes

The determination of α_S from jet rates and event shape distributions is reviewed by J. Schieck in these proceedings. The LEP experiments have coordinated their final event shape analyses via a working group (LEP-QCDWG) yielding directly comparable consistent results ¹. The re-analysis of JADE data uses the methods developed at LEP and thus the results can also be compared directly ¹. All analyses including the older TOPAZ study ¹⁹ are based on NLO QCD calculations combined with resummed NLLA calculations leading to more stable results.

The availability of NLO QCD predictions combined with resummed NLLA calculations for the 4-jet fraction with the Durham or Cambridge jet algorithms lead to precise measurements of α_S ^{20,1} from the LEP experiments and from JADE data.

10. e^+e^- Fragmentation

In ¹ data from LEP experiments were used to update the measurement of α_S from the cross section σ_L for hadron production via a longitudinally polarised virtual Z^0 or γ . A combination of results for α_S from analyses of the scaling violation of charged hadron momentum spectra was done in ¹. The data are from LEP and lower energy experiments. Both measurements are based on NLO QCD.

11. $pp/p\bar{p}$ Scattering Processes

Both results stem from analysis of $p\bar{p}$ collisions by the CERN SppS collider experiments UA1 and UA6. The cross section for production of final states with b-jets is determined with a cut on the angle between the two b-jets ²¹. Due to this cut the cross section measurement becomes sensitive to α_S ; a NLO QCD prediction is used to extract α_S .

The cross section difference $\sigma(p\bar{p} \rightarrow \gamma X) - \sigma(pp \rightarrow \gamma X)$ is sensitive to the parton process $q\bar{q} \rightarrow \gamma g$. Together with DIS data to constrain the valence quark pdfs α_S can be determined ²².

12. ICHEP 2006 World Average

The final ICHEP 2006 world average is calculated from the values for $\alpha_S(m_{Z^0})$ shown in table 1 for each class of analyses. In case of several analyses in a class the intermediate average as shown in table 1 is used. The statistical, experimental and soft QCD errors are assumed to be uncorrelated and the hard QCD errors are assumed to be partially correlated. The intermediate and final averages are shown in figure 1. The final average is dominated by the LQCD result with

$\chi^2/\text{d.o.f.} = 17/9$ and $P(\chi^2) = 0.05$. Without the LQCD result the average is $\alpha_S(m_{Z^0}) = 0.1200 \pm 0.0019$ with $\chi^2/\text{d.o.f.} = 14/8$ and $P(\chi^2) = 0.07$. Our average is consistent with other recent results ^{14,23}. The small values for the χ^2 probabilities might indicate that the systematic errors in some of the analyses are estimated aggressively.

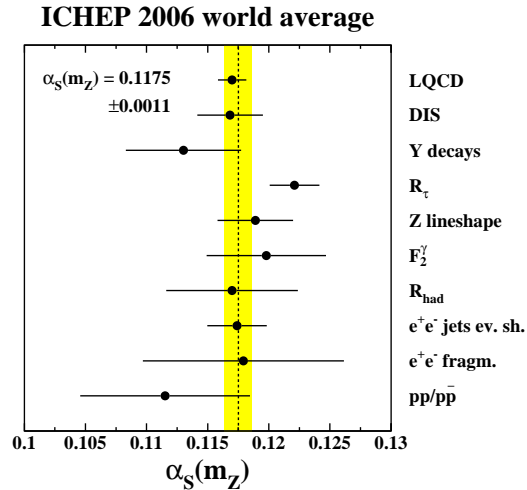


Fig. 1. Intermediate averages of $\alpha_S(m_{Z^0})$ from each class of analyses as shown in table 1. The dashed vertical line and grey band indicate the final average with total errors.

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Table 1. Results for $\alpha_S(m_{Z^0})$ from various analyses as indicated. The values of Q refer to the energy scales where the measurements were performed.

Process	Q [GeV]	Theory	$\alpha_S(m_{Z^0})$	$\pm\text{stat.}$	$\pm\text{exp.}$	$\pm\text{soft}$	$\pm\text{hard}$
Lattice QCD ³	1.5-7.5	NNLO	0.1170	0.0007	-	0.0002	0.0009
F_2^{ep} ^{4,5}	1.87-15.2	NNLO	0.1166	-	0.0009	0.0006	0.0018
pol. SF ⁷	91.2	NLO	0.113	0.004	-	0.004	0.007
F_3^ν ⁶	2.2-11	NNLO	0.119	0.002	0.005	0.001	0.004
Bjorken SR ⁸	1.58	NNLO	0.1217	0.0026	0.0092	0.0029	0.0006
GLS SR ¹¹	1.73	NNLO	0.1123	0.0048	0.0066	0.0045	0.0006
$ep \rightarrow \text{jets}$ ¹²	8.5-60	NLO	0.1186	-	-	0.0011	0.0050
DIS av.	-	-	0.1168	0.0002	0.0009	0.0006	0.0025
$R_b(s)$ ¹³	4.75	NNLO	0.1191	-	0.0038	-	0.0038
$R_{Y \rightarrow \gamma\text{gg}}$ ¹⁴	4.75	NNLO	0.1097	-	0.0032	-	0.0032
Y decays av.	-	-	0.1130	-	0.0033	-	0.0034
R_τ ¹	1.777	NNLO	0.1221	-	0.0006	0.0004	0.0019
Z^0 Lineshape ^{1,16}	91.2	NNLO	0.1189	-	0.0027	-	0.0015
F_2^γ ¹⁷	1.38-27.9	NLO	0.1198	-	0.0028	-	0.0040
R_{had} ¹⁸	2	NNLO	0.117	-	0.005	-	0.002
JADE ev. sh. ¹	14-44	NLO+NLLA	0.1203	0.0007	0.0017	0.0053	0.0050
TOPAZ ev. sh ¹⁹	58	NLO+NLLA	0.1219	0.0036	0.0008	0.0015	0.0047
LEP ev. sh. ¹	91.2-206	NLO+NLLA	0.1202	0.0005	0.0008	0.0019	0.0049
JADE R_4 ²⁰	14-44	NLO+NLLA	0.1159	0.0004	0.0012	0.0024	0.0007
LEP R_4 ¹	91.2-206	NLO(+NLLA)	0.1175	0.0002	0.0010	0.0014	0.0015
$e^+e^- \rightarrow \text{jets}$ ev. sh. av.	-	-	0.1174	0.0002	0.0010	0.0015	0.0016
$e^+e^- \rightarrow \sigma_L$ ¹	91.2	NLO	0.1169	-	0.0035	0.0018	0.0072
$e^+e^- \rightarrow \text{sc. viol.}$ ¹	91.2-206	NLO	0.1192	-	0.0056	-	0.0070
$e^+e^- \rightarrow \text{fragm.}$ av.	-	-	0.1179	-	0.0040	0.0010	0.0071
$p\bar{p} \rightarrow b\bar{b}X$ ²¹	20	NLO	0.1130	-	0.0065	0.0050	0.0067
$pp/p\bar{p} \rightarrow \gamma X$ ²²	24.3	NLO	0.1112	0.0016	0.0033	0.0039	0.0039
$pp/p\bar{p}$ av.	-	-	0.1115	0.0013	0.0034	0.0039	0.0044
ICHEP 2006 av.	-	-	0.1175	0.0006	0.0001	0.0002	0.0009

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